UWB TIMING SYNCHRONIZATION USING DIRTY TEMPLATES

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I. Introduction

Precise localization and reliable exchange of information among distributed sensors, soldiers and unmanned aerial/ground vehicles (UAVs/UGVs) are important for tactical communications. To this end, Ultra-Wideband (UWB) technology emerges as a promising candidate, providing high performance wireless links with low complexity and low probability of detection (LPD). Rapid timing synchronization constitutes a major challenge in realizing these promises. Synchronization faces accentuated difficulties in the UWB regime because its waveforms are impulse-like and have low amplitude, and the propagation channel is unknown at the receiver. These explain why synchronization has attracted so much interest in UWB research [3], [1], [4], [6], [5]. But each of existing approaches requires a number of restrictive assumptions.

Without invoking any of the assumptions required by existing algorithms, we develop timing algorithms that remain operational in general UWB settings with fast time hopping (TH), *unknown* multipath propagation and even when multiple users are present. Our synchronizers rely on symbol-rate samples and thus entail low complexity. Most existing synchronizers are based on the unique maximum of the received pulse's autocorrelation function, which requires a "clean template" of the received pulse to be available. The latter is not feasible when the multipath channel is unknown. Our novel criterion relies on the unique maximum that emerges by cross correlating "dirty templates" extracted from the received waveform. These dirty templates render channel information unnecessary since it is embedded in the received waveform.

II. Timing with Dirty Templates (TDT)

A. System Model

In UWB multiple access, every symbol duration T_s consists of N_f frames. During each frame of duration T_f, a data modulated $T_p(\ll T_f)$-long pulse $p(t)$ is transmitted. For conciseness, we will deal with pulse amplitude modulation (PAM) where the kth symbol from the uth user $s_u(k)$ is drawn equi-probably from $\{\pm 1\}$. User separation is accomplished with pseudo-random TH codes $c_u(n)$. The multipath channel for user u has $L_u + 1$ taps whose delays satisfy $\tau_{u,0} = 0$ and $\tau_{u,l} < \tau_{u,l+1}$. The waveform arriving at the receiver is then given by:

$$r(t) = \sum_{u=0}^{N_u-1} \sqrt{\mathcal{E}_u} \sum_{k=0}^{+\infty} s_u(k) p_{u,R}(t - kT_s - \tau_u) + \eta(t), \tag{1}$$

where N_u is the total number of active users, τ_u is the propagation delay of the uth user's direct path, $\eta(t)$ denotes zero-mean additive Gaussian noise (AGN), and $p_{u,R}(t) := \sum_{l=0}^{L_u} \alpha_{u,l} \sum_{n=0}^{N_f-1} p(t - nT_f - c_u(n)T_c - \tau_{u,l})$ denotes the overall *received* symbol-long waveform capturing the pulse shaper and the dispersive channel effects. Timing synchronization amounts to finding the desired user's timing offset $\tau_u \in [0, T_s)$ for the desired user. Notice that the AGN $\eta(t)$ is white Gaussian noise with PSD $\sigma^2/2$, but bandpass filtered by the receiver frontend with bandwidth B and center frequency f_0. We assume that:

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(as) *The nonzero support of the waveform* $p_{u,R}(t)$ *is upper bounded by the symbol duration* T_s.
This assumption implies that inter-symbol interference (ISI) is absent, but allows inter-pulse and inter-frame interference to be present. In low-duty-cycle UWB systems, (as) is satisfied by choosing $T_f \geq \tau_{L,0} + T_p$ and $c_u(N_f - 1) = 0$; whereas in high-rate UWB radios, the condition $T_f \geq \tau_{L,0} + T_p$ can be relaxed as long as guard frames are inserted between symbols to avoid ISI, much like zero-padding in narrowband systems.

B. Dirty Templates

Our idea for estimating τ_u hinges upon pairs of successive symbol-long segments of $r(t)$ taken at candidate time-shifts $\tau \in [0, T_s)$. Integrate-and-dump operations are performed on products of such segments to obtain *symbol-rate* samples: $x(k;\tau) = \int_0^{T_s} r(t + 2kT_s + \tau) r(t + (2k-1)T_s + \tau) dt$. The symbol-long segments $r(t + 2kT_s + \tau)$ and $r(t + (2k+1)T_s + \tau)$, for $t \in [0, T_s)$ serve as "templates" for each other in the correlation operation. We call these templates "dirty" because: i) they are noisy; ii) they are distorted by the *unknown* channel; and iii) they are subject to the *unknown* offset τ_0. The latter constitutes a major difference between our TDT and the transmitted reference (TR) approach [2] for channel estimation and symbol demodulation.

C. TDT Algorithms

Focusing on a point-to-point (PTP) link and treating multi-user interference as noise, we establish:

Proposition 1: *Under (as), unbiased and mean-square sense (mss) consistent (non-)data-aided TDT can be accomplished even when TH codes are present and the UWB multipath channel is unknown, using "dirty"* T_s*-long segments of the received waveform as follows:*

$$\hat{\tau}_{u,ptp} = \arg \max_{\tau \in [0,T_s)} \frac{1}{K} \sum_{k=1}^{K} \left(\int_{2kT_s}^{(2k+1)T_s} r(t+\tau) r(t+\tau-T_s) dt \right)^2 . \tag{2}$$

The synchronizer (2) is operational in a blind mode. But synchronization is possible with a minimum of four symbols adhering to the following training pattern:

$$s_u(k) = (-1)^{\lfloor k/2 \rfloor}. \tag{3}$$

More important, this training pattern also enables TDT in a multi-user (MU) environment:

Proposition 2: *Under (as) and with the desired user transmitting the training pattern in* (3) *while other users transmit zero-mean i.i.d. information symbols, mss consistent data-aided TDT can be accomplished with as few as four training symbols, using either*

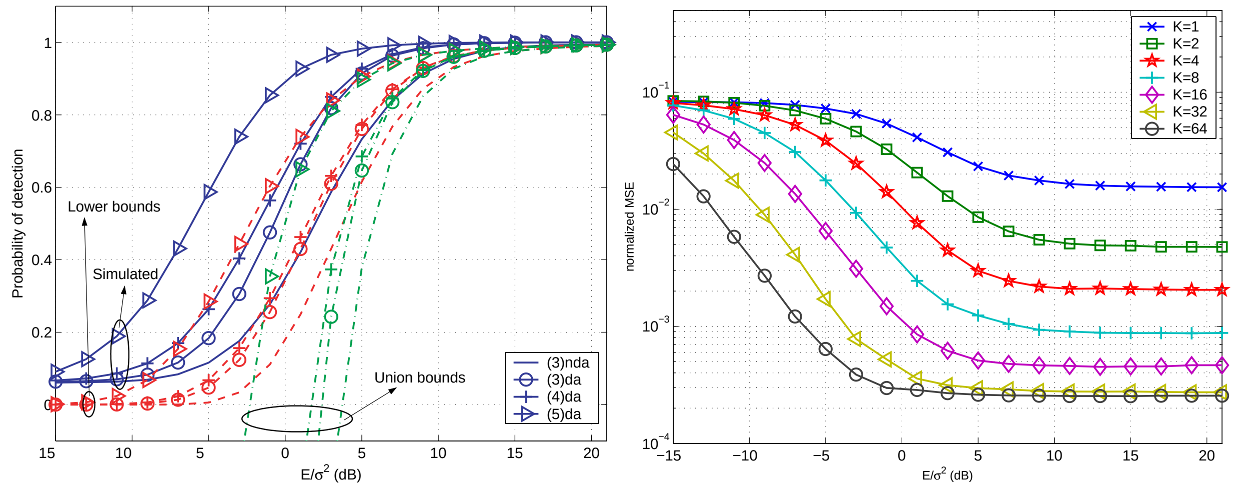
$$\hat{\tau}_{u,mu1} = \arg \max_{\tau \in [0,T_s)} \left(\frac{1}{K} \sum_{k=1}^{K} \int_{2kT_s}^{(2k+1)T_s} r(t+\tau) r(t+\tau-T_s) dt \right)^2 , \tag{4}$$

or

$$\hat{\tau}_{u,mu2} = \arg \max_{\tau \in [0,T_s)} \left(\int_0^{T_s} \bar{r}(t+\tau) \bar{r}(t+\tau-T_s) dt \right)^2 , \quad \bar{r}(t) := \frac{1}{K} \sum_{k=1}^{K} (-1)^k r(t + 2kT_s), \tag{5}$$

without requiring any knowledge on these users' channels or timing information.

Two remarks are in order here with regards to the performance-complexity tradeoff: i) established for TDT in a MU environment, synchronizers (4) and (5) can further improve performance when applied to a PTP link; but unlike (2), they rely on the training pattern (3); and ii) though (5) yields the best performance, it requires averaging analog waveforms.



(a) (b)

Fig. 1. (a) Probability of detection and lower bounds vs. SNR with $K = 8$, in a PTP link (nda: non-data-aided, da: data-aided); and (b) Normalized MSE for (5) with various K values, in a MU environment.

D. Preliminary Simulations

In Fig. 1(a), the simulated probability of detection vs. SNR together with its analytical lower bound are shown with $K = 8$. The lower bounds are rather pessimistic, but they correctly predict the relative performance of these synchronizers. The union bounds are also shown. They are too loose to give meaningful indications at low-to-medium SNR. In Fig. 1(b), the normalized MSE corresponding to (4) in the presence of two interfering users is plotted. The two interfering users are asynchronous relative to the desired user.

III. Conclusions

In this paper, we established a novel criterion for UWB timing synchronization, that we termed TDT. For a point-to-point link, we developed low-complexity TDT algorithms with and without training symbols and compared their performance by analysis and simulations. In addition, we designed a simple training pattern which not only provides speedup for timing a single-user, but also enables timing a desired user in a multi-user setup. Relying on simple integrate-and-dump operations as TR, our TDT algorithms provide timing information that is needed by TR without incurring TR's severe loss in spectral efficiency.

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